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Generating electricity from the oceans

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ABSTRACT

Ocean energy has many forms, encompassing tides, surface waves, ocean circulation, salinity and thermal gradients. This paper will considers two of these, namely those found in the kinetic energy resource in tidal streams or marine currents, driven by gravitational effects, and the resources in wind-driven waves, derived ultimately from solar energy. There is growing interest around the world in the utilisation of wave energy and marine currents (tidal stream) for the generation of electrical power. Marine currents are predictable and could be utilised without the need for barrages and the impounding of water, whilst wave energy is inherently less predictable, being a consequence of wind energy. The conversion of these resources into sustainable electrical power offers immense opportunities to nations endowed with such resources and this work is partially aimed at addressing such prospects. The research presented conveys the current status of wave and marine current energy conversion technologies addressing issues related to their infancy (only a handful being at the commercial prototype stage) as compared to others such offshore wind. The work establishes a step-by-step approach that could be used in technology and project development, depicting results based on experimental and field observations on device fundamentals, modelling approaches, project development issues. It includes analysis of the various pathways and approaches needed for technology and device or converter deployment issues. As most technology developments are currently UK based, the paper also discusses the UK's financial mechanisms available to support this area of renewable energy, highlighting the needed economic approaches in technology development phases. Examination of future prospects for wave and marine current ocean energy technologies are also discussed.

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1. Introduction

Energy resources, the implications of their depletion and price fluctuations are currently at the forefront of the global energy debate. Energy needs, their associated security of supply coupled with environmental issues and the impact of climate change will require policies to exploit non-polluting natural sources. There is now an urgent need to support our energy generating capacity through the development of low carbon technologies, especially those from renewable resources. Fulfilment of such needs through the low carbon route is not only central to sustainable development but also necessary for emissions reductions. It is clear that the promotion of such approaches is now taking pace globally and that the current economic climate offers a further window of opportunity for expanding the utilisation of renewable energy technologies through the various stimuli packages initiated by many governments around the world.

Ocean energy has many forms – tides, surface waves, ocean circulation, salinity and thermal gradients. The focus of this paper is dedicated to two of these. Those found in tidal or marine currents, driven by gravitational effects, and wind-driven waves, derived ultimately from solar energy.

Globally, tidal dissipation on continental shelves has been estimated at 2.5 TW [1]. Considering the UK, which is currently considered the world's leader in the technological conversion of ocean energy resources; the waters around its shoreline are estimated to dissipate approximately 10% (0.25 TW) of the tidal resource. If one tenth of this figure could be tapped for power generation (which would undoubtedly require a very large capital investment), tidal stream or marine current power could deliver around 220 TWh/annum, which roughly equates to half of the UK's current electricity consumption. Whilst most incident wave energy is dissipated in deep water, where economic exploitation is yet to be demonstrated, there is nevertheless a significant nearshore resource estimated by the European Thematic Network on Wave Energy at 1.3 TW globally, with a technically exploitable resource of 100–800 TWh/annum [2]. The UK has amongst the most energetic of wave climates, which could provide up to 50 TWh/annum [3].

Ocean energy resources derived from wind, waves, tidal or marine currents can be utilised and converted to large scale sustainable electrical power. Conversion systems are easily adaptable and can be integrated within the current utility power supply infrastructure and networks. However, in the development of renewable energy technologies, many countries have embarked on policies that are highly reliant on the expansion of large-scale off-shore wind energy to electrical power, with only small attention being directed to other areas of renewable energy. This imbalance, although understandable, as wind technologies are far more mature, it is important not to marginalise the utilisation of other ocean resources by concentrating effort and diverting the available financial resources to off-shore wind only.

This work aims to convey the research and development aspects of the conversion of marine current and wave energy resources. In addition, this work establishes a step-by-step approach that could be used in technology and project development, depicting results based on experimental and field observations on device fundamentals, modelling approaches, project development issues as well as a discussion of the financial mechanisms available to support this area of renewable energy. It further highlights the economic approaches needed in the development phases of devices and projects and provides a brief overview of future prospects of utilising the wave and marine current resources. The aim here is to provide an insight, linked to evidence into the various stages and prospects for wave and marine current technology development and delivers an overarching appraisal of the salient issues to people interested in this important area of renewable energy.

2. Wave energy conversion

Ocean energy resulting from the exploitation of marine currents or waves can be extracted by a variety of technology concepts. Wave energy conversion stems from wave motion and is related to the wave height and period, the technology variants are many, each of which is aimed at exploiting the various properties of wave action.

Deep water sea waves offer large energy fluxes under predictable conditions over periods of days. The energy E (Wh), per unit wavelength in the direction of the wave, per unit width of wave front is given by:

$$E = \frac{1}{16}\frac{\rho g^2}{\pi}(H^2T^2) \tag{1}$$

This is the total excess energy in continuous wave motion in deep water (kinetic + potential) in a dynamic sea [4], where ρ is the density of sea water (kg/m^3), g is the acceleration due to gravity (ms^{-1}), H is the wave crest height (m) and T is the wave period (s^{-1}).

The power P per unit width of a wave front is given by:

$$P = \frac{1}{64}\frac{\rho g^2}{\pi}(H_s^2T_e^2) \tag{2}$$

where P is in W/m, H_s is the significant wave height (m) and T_e is the wave period [4]. More in-depth analysis of the fundamentals can be found in the now standard text book on wave energy conversion [5] and a recent status of energy conversion technologies from waves is given in [6].

Wave energy is inherently stochastic being a consequence of wind energy. The conversion of wave energy into usable energy is extremely complex due to the hydrodynamic processes presented in the diffraction and radiation of waves as they propagate to shore. In essence the conversion to electrical power is subject to hugely varying energy flux, and time scales (few seconds in wave action and hour or days in sea states) that the conversion technology need to cope with and, once conversion occurs, conditioning the generated power to the 50 or 60 Hz of the electrical utility grid also is a challenge. The conversion is established through what is known as a power take-off (PTO) system, such as an air turbine, power hydraulics, electrical generator and other variants that can be exploited for the production of usable energy.

Furthermore, operating any technology in the sea comes with the penalty of ensuring survivability of the device and wave energy converters are no exception. Hence wave energy and marine current converters (Section 3) will need to be designed to withstand the most severe conditions expected in their lifetime. For instance, the wave energy concepts being developed vary greatly and since it is not possible to predict with great accuracy the severity of a storm at a certain location, a probabilistic approach will be needed to determine design conditions and the acceptable level of risk for the device being developed [6].

3. Marine current energy conversion

As indicated earlier, marine currents are a form of kinetic energy. Although this energy is generally diffuse, it is concentrated at a number of sites where sea flows are channelled around or through constraining topographies such as islands and straits. There are many potential sites around the world that could be explored and utilised. The tides which drive such currents are highly predictable, being a consequence of the gravitational effects of the planetary motion of the earth, the moon and the sun.

As the resource is highly predictable albeit variable in intensity, its conversion to useable energy offers an advantage over other renewable energy resources – such as wind or wave energy [7,8]. Projects that relay on marine currents will have quantifiable and firmly foreseeable output profiles which can be plan for and managed appropriately within utility grid. In addition, long term energy yields can be accurately estimated which offer a particular advantage to a project developer to negotiating, with utilities, a better power purchasing agreement compare with other renewables.

Utilising marine currents does not require water-impounding structures such as dams used in conventional hydropower but some sort of anchoring system within the flow stream. In most cases, the fundamental understanding needed has similar basis as those used to predict the conversion of the kinetic energy of a moving fluid to provide useful work as employed in wind energy conversion. Hence its technology variants are somehow similar or related to those of wind energy conversion although other unique design philosophies are being pursued, as discussed further below.

3.1. Energy extraction from marine currents conversion

Marine currents offer an analogous energy resource to wind; i.e. the kinetic energy of the moving fluid can similarly be extracted and applied using a suitable type of turbine rotor. The analysis offered for consideration of wind turbines can be extended for marine current turbines. The power P_o (W) available from a stream of water (in the absence of significant changes in depth or elevation) is given by:

$$P_o = \tfrac{1}{2}\rho A v_o^3 \tag{3}$$

where ρ (kg/m^3) is the density of fluid, A (m^2) is the cross-sectional area of the rotor under consideration and v_o (m/s) is the unperturbed fluid speed.

Eq. (3) shows that P_o is proportional to the cube of the fluid velocity; the consequence of this is that the power and hence the energy produced are highly sensitive to variation in the fluid velocity. In addition, the power in the flow is also promotional to the fluid density, which for water, is about 800 times that of air. This indicates that the power density or flux (kW/m^2) for marine current energy converters will be appreciably higher than that produced by wind energy converters when considered at appropriately rated speeds for both technologies [7]. The consequence of this is that smaller and hence more manageable converters can be installed to exploit local conditions, such as water depth or bathymetry where they are favourable. However, water depth in practice places a constraint on the maximum rated power of a marine current turbine. Such a constraint does not exist with wind turbines.

Considering power extraction using the case of a horizontal-axis turbine, the theory of which stems from the classic analysis of power extraction from the wind by an actuator disk [9] is normally used. This states that the maximum power that can be extracted by a single turbine in an unconstrained flow is the fraction (16/27 = 0.59) of the kinetic energy flux through the rotor disk area and in the case of no extraction this is given by Eq. (3). In general, this fraction is known as the power coefficient C_p, defined by:

$$C_p = \frac{P}{P_o} = \frac{P}{(1/2)\rho A v_o^3)} \tag{4}$$

where P is the power developed by the generator. For all wind turbines currently in operation, $C_p < 0.59$; however, more sophisticated design methods allowing for the effects of finite numbers of blades predict for typical designs, maximum values of C_p in the range 0.4–0.5 [9,10]. Such analysis also applies to the case of similar turbines in a marine current sites or tidal stream channels, providing these are wide and deep compared to the rotor disk diameter and that there is only a small change in free surface elevation across the turbine location [10,11].

The power coefficient as given in (4) represents the effectiveness of a device in generating power, regardless of flow speed or capture area of the device. C_p can also be determined experimentally from the consideration of the relationship between the fluid speed and the rotational speed of the turbine blades. This known as the tip speed ratio, TSR, given by:

$$\mathrm{TSR} = \frac{\omega R}{v_o} \tag{5}$$

where R (m) is the radius of the turbine and ω (rad/s) is the rotational speed of blade tip.

Another important parameter for marine current turbines is the thrust T encountered by the hydrodynamic subsystem. This is normally quantified in terms of the thrust coefficient C_t and is given by:

$$C_t = \frac{T}{(1/2)\rho A v_o^2} \tag{6}$$

C_t represents the loading of the subsystem, independent of scale and is also a function of TSR.

It is important to note that in spite of the analogy indicated above with wind turbines, there are major differences in the engineering of marine current turbines. This is particularly due to the higher density of water compared with air, the closer proximity of the free surface and the much slower speed of flow and cavitation. Hence, marine current turbines will encounter larger forces than wind turbines and the design of marine current converters will need to take into account the overall thrust from the kinetic energy of the flowing water. Installations of such converters in fast flowing seas will clearly present structural engineering challenges for both system integrity and foundations or anchorage of the submerged structure. Such structural designs will need to take into account the marine environment and the complex dynamic loadings that are present due wave/structure interactions, turbulence, velocity shear and pressure variations across a vertically moving rotor within the bathymetry (water column) of the flow regime.

4. Technology development issues

There are thriving research and development communities and device developers around the world undertaking both fundamental, applied research and technology development of both wave and marine current energy conversion. However, at present most technological innovations aimed at exploiting such resources are currently at early stage of development, with only a handful of devices that can be classified to be at the commercial pilot demonstration stage. Due to the characteristic of the resource and the infancy of the concepts currently employed for conversion, there is a plethora of conversion technologies with unconnected design philosophies that seem to dilute effort and compete for the scarcely available financial resources. This, in many cases, coupled with the fact that most developers are small enterprises with limited funds,

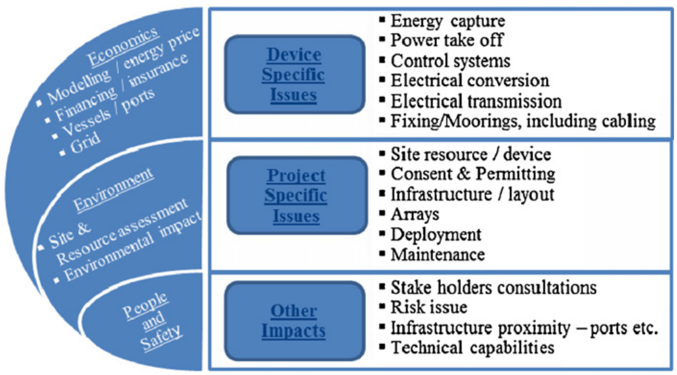

Fig. 1. Important issues: device and project development.

has resulted in high inertia holding back a faster trajectory to accelerate technology commercialisation.

Nevertheless, in order to understand the salient issues in developing such ocean energy technologies, there are various specific areas that will need to be considered for developing the wave and marine current energy conversion technologies and associated project deployment. Fig. 1 highlights specific areas in terms of their relationship to the technology (device) or a project development (site and any associated environmental impacts). The former is related to the conception of the original idea and its development whilst the latter is more related to deployment at a pilot/commercial scale in the sea.

For a conversion device to be thoroughly developed, it will need to go through various steps of controlled scaled testing in laboratories and should be subjected to Technology Readiness Level (TRL) or assessment protocols [12–15].

To deploy a device or multiple devices in the sea will need higher level of funding as well as a comprehensive and meticulous planning. The processes involved will require a developer to identify a project site, undertake the various steps needed to obtain consent and permitting and have a robust plan for deployment and maintenance. Energy production and hence income will obviously be the main focus for selecting the site due to its partially known energetic potential: high or moderate flow velocity or energetic wave climate. In addition, there are many factors which also need consideration: weather window for deployment, understanding of sea bed conditions, availability of vessels, proximity to a grid connection and ports. In most case, especially in the UK, the grid connection issue is similar to that encountered with other renewable energy technologies such as offshore wind and hence will not be discussed here.

It is worth mentioning that unlike fossil fuelled electricity generation, the fuel – water flow or waves – for producing electricity is free and the revenue stream is governed by the energy yield of the project. Generally, and as can be seen from Fig. 1, the overall cost of an ocean energy project – wave or a marine current – will likely to be dominated by capital and operating costs including upfront cost of consenting, surveys etc. Since the revenue is mainly dependent on the flow or wave conditions, the profitability of a project is highly dependent on clear understanding of site conditions including flow field characteristics. Hence resource and site assessments will be crucial in any economic analysis of the viability or otherwise of an ocean energy project.

The following sections aim to convey the needed understanding for the developmental issues summarised and depicted in Fig. 1. They provide step-by-step approach to the salient issues, establishing methodologies, reporting on the currently available results and illustrate pathways to gain the necessary understanding of the subject.

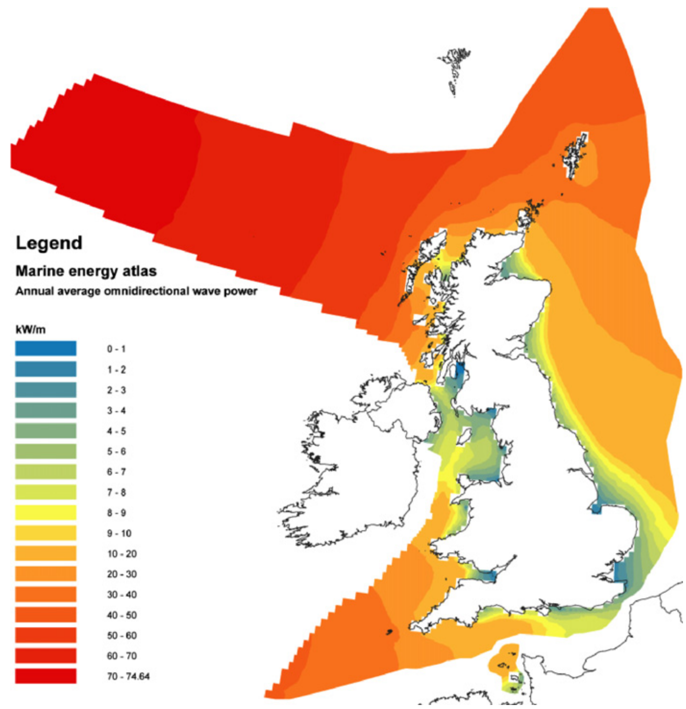

Fig. 2. Annual mean wave power full wave field charts recreated from the Atlas of UK Marine Renewable Energy Resources [16]

4.1. Resource assessment

As indicated above the assessment of the ocean energy resource is one of the most important aspects for determining the profile of a successful project. Countries such as the UK and Ireland have embarked on producing their own national atlases of the wave and marine currents resources around their shores. These are given in terms of contour plots of the resource, as shown in Figs. 2 and 3, giving the annual mean wave power and the average marine current power respectively for the UK shores [16]. However, such atlases reflect coarse data and are inappropriate for the exploitation of a specific site. Much more detailed data will need to be gathered and analysed from the site prior to project commencement. Furthermore, resource assessments produced by developers tend to be subject to commercial confidentiality and current methodologies tend to relay on sparsely available data – such as tidal diamonds and wave rider buoys which do not give spatially representative estimates of the resource that are acceptable for accurate energy yield determination at a particular site. If no site specific data is available, a possible way forward is to undertake a combination of historically available data sets and computer simulation to characterise the resource. Such techniques can be employed to arrive at appropriate estimates of the resource with better level of confidence than those derived from atlases. These methodologies are at early stages of development and being standardised through protocols, co-ordinated by academia and industry [17].

In wave energy the resource is a consequence of the wind and has the similar but less sever drawbacks in terms of its variability and predictability. The meteorological study of wave climate is a complex process involving many factors. The main limitation of determining energy performance of a device at a specific site is the lack of available in situ measurement of the resource. However, this shortcoming can be overcome by the application of numerical wave model data or satellite remote sensing measurements [18].

For the purposes of estimating the energy yield of a device it is useful to describe its response in terms of a small number of param-

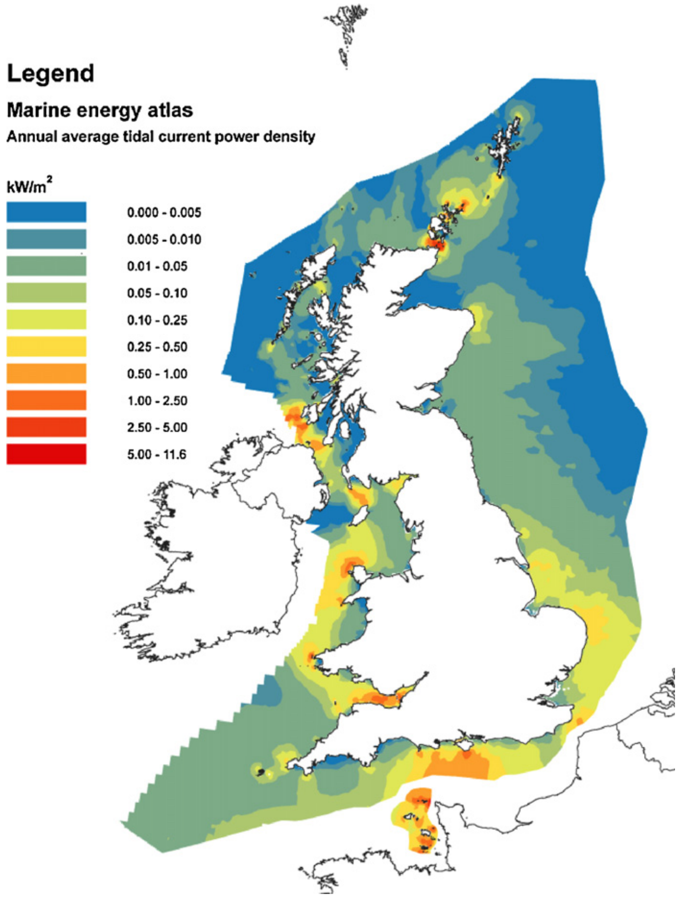

Fig. 3. Average tidal power charts recreated from the Atlas of UK Marine Renewable Energy Resources [16].

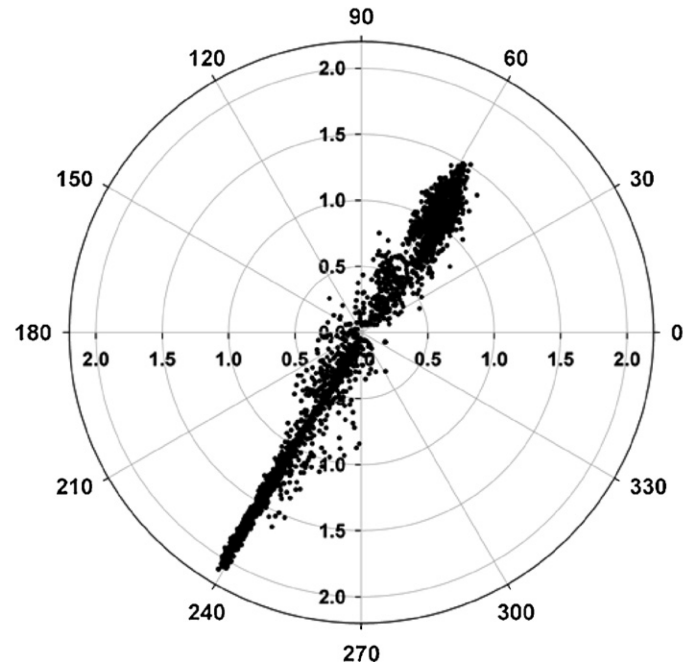

Fig. 4. Measured resource data of marine current showing velocity intensity and direction for a site around the Isle of Wight, UK.

eters. Device performance is normally given in the form of a 'power matrix' in terms of significant wave height H_s and period T_e. The wave data sets available for these parameters have different characteristics and limitations [19,20] but are normally obtained from: (a) in situ measurements – typically wave rider buoy data collected from various sites around the world providing a temporal average of waves at a point or over a small area, (b) satellite remote sensing – provide a near-instantaneous average of waves over an area of several square kilometres and (c) numerical wave models – provide an estimate (rather than measurement) of the wave spectrum which can be interpreted statistically as an average over both area and time. The power in the waves is usually expressed in kilowatts per unit length (kW/m) of wave crest and a good location will have an annual average typically in the range 20–70 kW/m.

As indicated earlier, the resource for marine current energy conversion is more easily predictable and reliable. Resource estimation can be achieved through direct measurements of tidal elevations or current velocities. In the former, databases exist giving measurements for tidal ranges as well as current velocities from tidal diamonds. Another important parameter in assessing a site for marine current energy conversion is the site depth or bathymetry as it governs the size of the device to be deployed and the number of devices within an array. Coarse bathymetry data can be obtained from generalised databases that exist for such parameters [21], or an hydrographic survey can return more accurate and higher resolution data.

Additional guidance for resource assessment is also provided by test centres such as the European Marine Energy Centre (EMEC) [22]. Given, an understanding of the bathymetry and due to the predictable nature of the resource, a measurement of the velocity over a period of one month is sufficient to allow quantification of device energy yields over the entire life of a device [23].

For marine current energy conversion, the gathering and analysis of field data for a specific site is generally undertaken by surveys of the site in which a number of Acoustic Doppler Current Profilers (ADCP) are deployed in favourable locations within the site. Fig. 4 gives the results of some of the information that can be gathered from such a deployment. The results shown is part of an on-going research by the author's team in which two ADCPs were deployed for the purpose of developing a project to exploit the resource within the site south of the Isle of Wight, UK. It must be stressed that many aspects of resource assessment remain the subject of research, such as the possible impacts on the site by the generators [24]; the interactions between devices in arrays or farms [25,26]; the effect of turbulence, and velocity profiles on the performance of devices [27,28].

4.2. Energy conversion philosophies

There is a plethora of wave and marine current energy conversions concept with different design and energy extraction philosophies. Hence it is unrealistic to establish a common approach to assessing these concepts. However, one can arrive at a common characterisation of operating principles which could be used to establish a class of technology within wave or marine current energy.

Typically, in wave energy there are categories that could be classed as (a) oscillating water columns (OWC), (b) overtopping devices and (c) wave activated bodies, sometimes known as oscillating bodies. A review of these is given in [6]. Marine current energy conversion systems are simpler and are typically classified as: (a) horizontal axis turbines (b) orthogonal flow turbines (c) variable foil systems and (d) venturi based systems. A detailed list of both wave and marine current technologies is given in [29].

Energy capture is achieved through a structure that converts the resource into mechanical energy and then through conventional rotating or linear generators- known as the power take off (PTO) into electrical power for supply to an electrical grid. In wave energy,

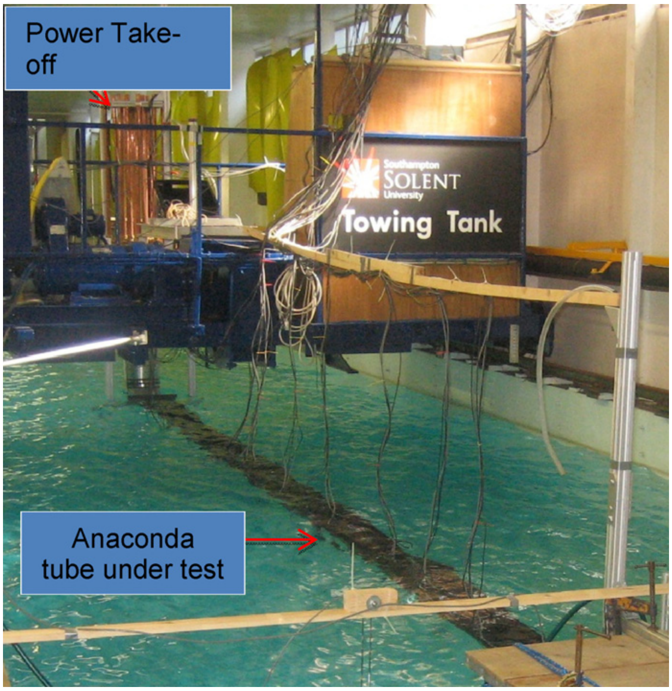

Fig. 5. 1/25th scale model of the Anaconda concept with PTO undergoing tests in a wave tank in Southampton [31].

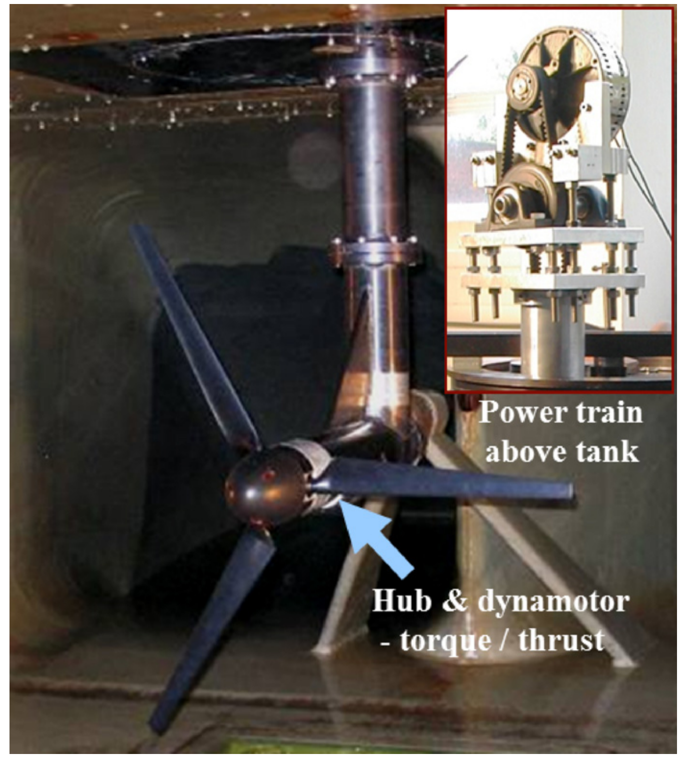

Fig. 6. 1/15th scale 0.8 m diameter model marine current turbine, undergoing tests in a cavitation tunnel.

air, water turbines as well as hydraulic motors can be used to provide the mechanical coupling that converts the alternate motion of the waves into a continuous one directional motion [6]. In marine currents, a rotor such as in a horizontal axis turbine can be used. Rotor design encompasses blade design, in which the mechanical motion is transferred to a type suitable for input to a stage where electrical power is produced. This sub-system may include a gearbox, a set of lever arms and pistons driving hydraulic fluid and or an electrical generator of a fixed or variable speed type. In most cases, the generated electricity is conditioned and transmitted to the grid through a subsystem which includes power electronics, transformers, circuit breakers and cables.

In both wave and tidal technologies it is important to de-risk the device development and take it through appropriate Technology Readiness Levels (TRLs) mentioned earlier. A good example of this is the process through which Pelamis Wave Power Ltd have taken their device testing, starting at 1/100th scale and culminating at the 1/7th intermediate scale demonstration model which used hydraulic power take-off systems which are functionally identical to those at full scale [30]. Such extensive testing conducted in both wave tanks and at sea was aimed at developing and proving the functionality of the hydraulics, control and data acquisition systems of the full scale device and to validate theoretical models.

Another exciting wave energy device is the Anaconda concept for which the fundamental aspects are currently being investigated at the University of Southampton [31]. The Anaconda consists of a closed rubber tube filled with water anchored head on to the waves in the sea. External waves establish pressure variations that result in the creation of bulge waves within the tube. Through a power take-off system at the stern of the tube, these bulge waves can be used to produce electrical power. Fig. 5 shows a 1/25th scale model of the device being tested within the 60 m long, 4 m wide and 2 m deep wave tank at the Southampton Solent University. The analysis and results of recent testing of the Anaconda can be found in [32].

In marine currents, rotor and blade designs are of major importance to our understanding of the fundamental interaction between the fluid flow and the device, the impact of cavitation and proximity of the sea bed and surface (boundary effects). Experimental and theoretical understanding will need to be generated at various scales of development. For instance, the work undertaken at the University of Southampton is addressing these issues covering device performance, cavitation and boundary effects of model marine current turbines. Model testing was undertaken on turbines with diameters in the range 0.3–0.8 m. This corresponds to 1/50th to 1/20th scales of a hypothetical 1st generation 16 m diameter marine current turbine. Rigorous testing of these model turbines was conducted in circulating water channels, towing tanks and cavitation tunnels. The latter was a facility at QinetiQ, Haslar, Gosport, UK, used to test 0.8 m diameter turbine with power take-off as shown in Fig. 6. The working section of the cavitation tunnel used was 5 m long, 2.4 m wide, 1.2 m high, pressure range 0.2–1.2 atmospheres and a maximum flow speed of 8 m/s.

Fig. 7 shows experimental and theoretical data of the power coefficient C_p as a function of tip speed ratio, TSR, for an instrumented 0.8 m diameter turbine, equipped with power take-off, for different yaw angles. The results shown in the figure highlights the expected optimal regions of operation (dotted) with the solid lines are the results of in-house developed blade element momentum theoretical model, representing a good fit with experimental data [33]. In addition to obtaining performance data as in Fig. 7 the impact of cavitation was also investigated. An example of the results obtained through observation of turbine operation in the cavitation tunnel is shown in Fig. 8 depicting blade cavitation encountered under certain conditions of flow. More details, giving the regions where this cavitation can occur, can be found in previously published work [33,34].

Additional work was also conducted to provide knowledge on the impact of wakes and device spacings in arrays. The experimental programme was conducted at two distinct scales so that fundamental research into flow effects could be conducted easily at in-house facilities whilst more complex experiments were performed at a large international water channel. Small-scale porous

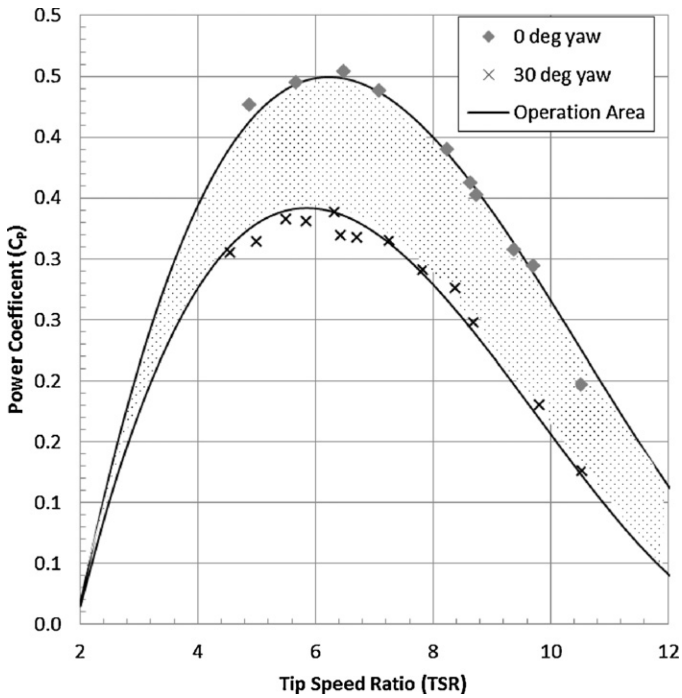

Fig. 7. Power coefficient C_p as a function of TSR for 0.8 m diameter model marine current turbine, blockage corrected, crosses are experimental results, solid line theoretical results.

actuator disc simulators were used to investigate key flow and device parameters such as proximity to sea bed/surface, flow velocity and inter-device spacing in both lateral and longitudinal directions. Much of this work was performed at the 21 m long (2 m wide and 1.5 m deep) tilting flume at the Chilworth Research Laboratory, University of Southampton. Dense three-dimensional flow maps of velocity and other parameters were acquired using high frequency acoustic flow measurement equipment. Near wake flow effects were measured using two 1/20th scale, fully-instrumented three-bladed marine current turbines in the IFREMER large water circulating channel facility (18 m long, 2 m deep and 4 m wide with flow velocities up to 2 m/s), Boulogne sur Mer, France. This latter aspect of testing focused upon the region of downstream flow that is heavily influenced by the rotating blades and turbine support structure. Full 3D flow maps were again acquired downstream

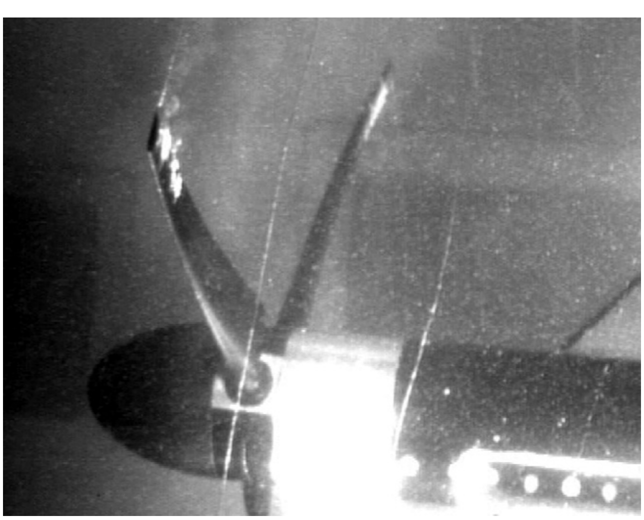

Fig. 8. Cavitation of three bladed model turbine under test in a cavitation tunnel (more details in [33,34]).

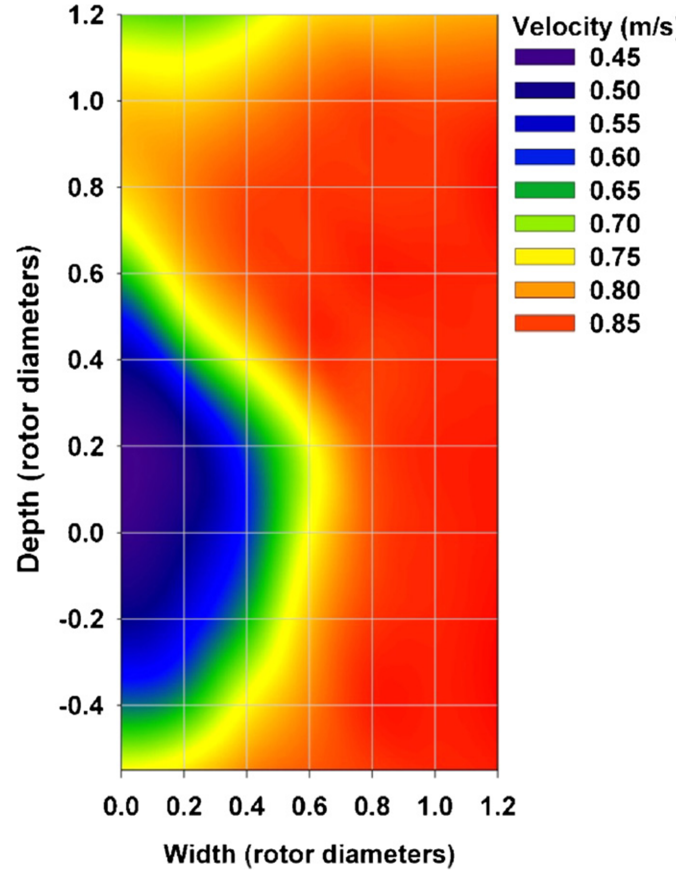

Fig. 9. Measured lateral plane velocity contours at 5-diameters downstream of a 1/15th-scale horizontal axis marine current turbine showing non-circular wake and the disturbance close to the water surface [35].

to better understand the observed flow effects around the energy extracting model turbine.

Fig. 9 shows an example of the measured velocity for a lateral plane, 5 diameters downstream of the rotor. The non-circular wake and the disturbance close to the water surface clearly indicate the influence of the device support structure upon the near wake region which will have implications for array design. In this work the key area of mapping centred on the wake that formed downstream of each turbine. This is a region of slow moving fluid that has extracted energy from the flow; it expands and gradually increases in velocity until, at a point far downstream, the wake has dissipated and the flow field returns to its undisturbed condition. The shape and intensity of the wake at varying distances downstream will determine the spacing between marine current turbines in farms or arrays at specific sites [35].

The results of the above experiments have highlighted disparities between our understanding of the operation of wind turbines (atmospheric-distant boundary) and marine current turbines (water depth restricted boundary). Fig. 10 shows experimental results for the downstream centerline velocity (normalized) for varying disk submergence depth. The results show that the seabed and water surface compress the tidal turbine's wake in the vertical plane. This means that numerical simulation methods originally developed for the axis-symmetric wakes of wind turbines will require modification [36]. Any constriction of the flow causes the wake to persist further downstream than initially expected. This means that tidal turbines will have to be spaced further apart than wind turbines. In addition, flow can be accelerated between two turbines positioned side-by-side in the flow (Fig. 11). Depending upon this lateral spacing and the water depth it may be possible to

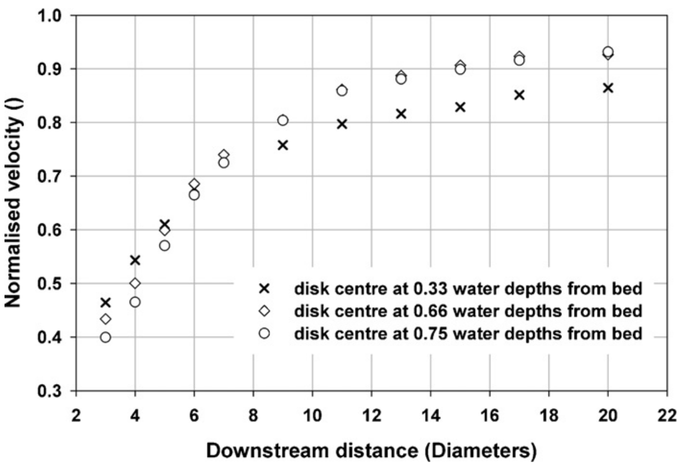

Fig. 10. Downstream centerline velocity (normalized) for varying disk submergence depth showing the effect boundary effects [36].

increase energy capture in an array by optimising the inter-device spacing of marine current turbines [37]. This seminal work has provided a base of information for future marine current turbine array design through both the above highlighted experimental studies and the development of software tools. Additional published work covering further details of these areas of research can be found in [38–40].

Approaches such those highlighted above signify that development of such devices requires not only the knowledge base to plan the testing needed and to understand the salient issues observed, but also the necessary testing facilities that are fit for the task and equipped with the appropriate level of instrumentation.

4.3. Interactions and impacts on the marine environment

An environmental assessment of a site is necessary to understand and evaluate the impacts and benefits of the introduction of the conversion technology into the sea zone in the area of interest. As indicated in Fig. 1, the assessment will need to include consultation with stakeholders and consenting authorities quantifying the intervention likely impacts from the inception to decommissioning. Such an assessment will inevitably contain site surveys and monitoring for the various phases of the project as can be seen in two developed projects one of wave energy site and the other of a marine current installation given in [41,42] respectively.

Environmental impact assessment of sites to be developed for wave or marine current energy extraction is also necessary as device foundations or anchors, profiles of structures and the resultant wakes are likely to change and influence the dynamics within the site including flow patterns and velocity intensity within the site. Issues such as sediment transport and deposition will need to be understood so that impacts can be established and designed for. Indeed, the impacts of installation and decommissioning phases and their established processes will also need to be quantified and addressed within an environmental impact assessment to be conducted by the developer.

In addition, site specific issues that may impact on the energy yield or the integrity of the device should also be identified. For instance, in marine currents, the velocity profile at a given site will vary significantly either due to eddies in the flow or due to the vicinity of other converters or turbines. This may give rise to turbulent effects which may: (a) result in systematic and appreciable loadings on the turbines that will contribute to device fatigue and vibration problems, and (b) impact on optimised layout of turbines working in arrays. Hence the effect of turbulence may require further study through test tank investigations with model turbines. Such studies will inform the design philosophy to allow for these impacts to be quantified and de-risked. Furthermore, as multiple devices or arrays are installed, site flow impedance and the impact of energy extraction will also need to be considered [43,44].

4.4. Installation, foundations and moorings

The experience and knowledge gained from oil exploration and extraction and now the installation of offshore wind turbines can be tapped and utilised in developing marine current and wave energy sites. Such knowledge can be adapted and applied to specific tasks such as deployments, the installation of the energy conversion devices, their foundations, moorings, cabling topographies and grid connection.

The first generation of wave energy conversion technologies is likely to be deployed offshore at water depths in the range 40 and 100 m. Such devices can be classified as floating bodies and as a result of wave motion, currents and wind they will be subjected to drift forces and therefore will need to be kept on station by moorings [45]. For marine current energy conversion most technologies are likely to be fixed by piling to the sea bed [46]. One of the main challenges is the implementation of these tasks in fast flowing streams in the sea. Hence slack and good weather window will be paramount for successful deployment. The use of jack-up barges has been successfully employed in deployment of early prototypes and remote foundation drilling is also been considered for new devices. Most devices have similar installation characteristics; providing opportunities for generic research to overcome these challenges.

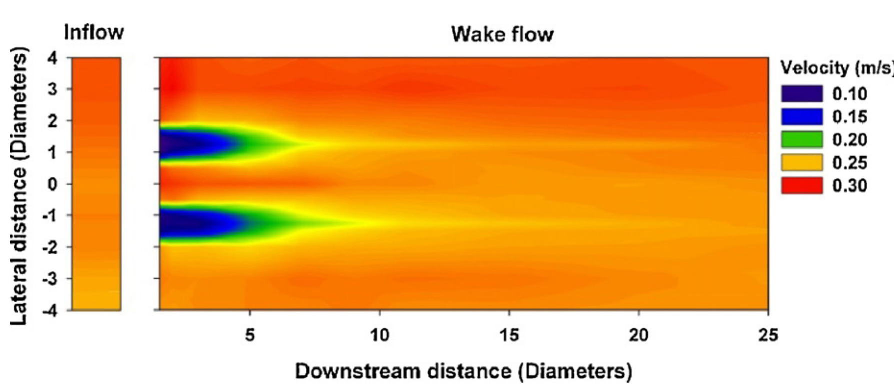

Fig. 11. Centre-height plan velocity field downstream of 2 side-by side actuator disks with lateral separation of 2.5-diameters (centre–centre) showing flow acceleration between the discs [37].

Fig. 12. World's 1st wavefarm of 3 P1-A, 750 kW each Pelamis machines installed at Aguçadoura, Portugal (image courtesy of PWP Ltd) [47].

5. Array and farms

Currently there are no farms or arrays of multiple devices operating in the sea. A notable exception which occurred in the second half of 2008, was the installation of the world's first grid connected wave farm composed of a set of three Pelamis P1 wave energy devices, deployed at Aguçadoura 5 km off the Atlantic coastline of northern Portugal (Fig. 12). This project had an installed capacity of 2.25 MW (consisted of 3 P1-A, 750 kW each), achieved proven installation of the units on a fully commissioned site infrastructure and successful export of power into the local grid [47]. The Aguçadoura wave energy project was supported by a specific feed-in tariff of approximately €0.23/kWh which was generous at the time. Unfortunately the project was abandoned for various reasons but mainly due to the financial collapse of the Australian-based infrastructure group Babcock & Brown which held a majority share in the project [48]. As will be seen from Section 8, this has not dented the efforts of the company as planning for larger projects of farms are underway within UK.

Nevertheless, it is anticipated that in the near future, the next phase in the development of wave and marine current energy devices will be the installation of multiple devices in array or farm configuration. This will allow experience to be gained at all stages of deployment, the production of appreciable power and a measure of the increasing scale effects (deployment, installation, connectivity, maintenance etc.) that are aimed at cost reduction and enhance experience within the operating environment.

5.1. Deploy-and-plug ocean zones

The provision of ocean zones in which all the difficulties of permitting and planning is taken care off by providing "*Deploy and Plug*" facilities for both device developers and utilities have been or being developed. There are at least two specific sites that are designed to provide such an option for developers – one in the UK and the other in Portugal.

The UK's Wave Hub, having an initial capacity of 20 MW that could be scaled up to 50 MW in the future, has become fully available for deployment of wave energy farms in November 2010 [49]. The Wave Hub facility is located 16 km off the coast of Cornwall in South West England and represents the world's largest test site for wave energy farms. There are four berths available for farms having a footprint of 1 km × 2 km each, established by the operating company which holds a 25-year lease (from the UK's Crown Estate) covering 8 km^2 of seabed. Marker buoys are installed to record and signal the Wave Hub's position. The plan is to grant a lease to developer/utilities for a term to be agreed. Grid-connection for devices is provided through an armoured subsea cable connected to a gravity based structure which consists of a 12-tonne steel chamber stabilised by bedrock in a 55 m water depth on the seabed. Cables are then extended from this structure to connect with devices using

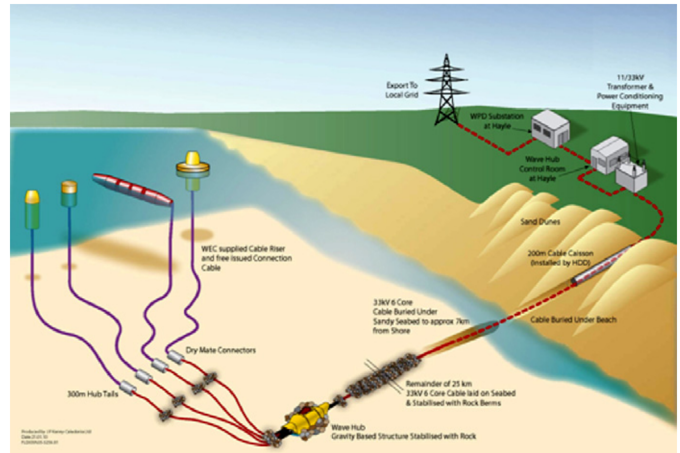

Fig. 13. World's 1st deploy-and-plug ocean zone installed at Wave Hub, UK (image of Wave Hub, www.wavehub.co.uk).

dry mate connectors and riser cables (Fig. 13). This is a £42 (US$63) million endeavour developed by the South West Regional Development Agency and is a cornerstone of its strategy to develop a world class marine energy industry in South West England and the UK. The first planned customer of this facility is to be Ocean Power Technologies, who plan to deploy its PowerBuoy wave energy converter within the site. However, to date no plans announced for a deployment date of the technology.

The second facility also in Europe is that of the Wave Pilot Zone (WPZ) announced by a Portuguese government decree in January 2008. The zone, which covers 320 km^2 is located between a 30 m and 90 m bathymetry contours, and is planned to be established in the west coast of Portugal about 130 km north of Lisbon. The initial phase is for a capacity of an 80 MW that in the future, could be expanded to 250 MW on the site. The development plan for the zone has indicated that a concession contract will be signed in 2010 with the aim of having the infrastructure in place by 2012 [50]. A recent announcement by the British Embassy in Lisbon indicated that the WPZ concession has been signed between the Portuguese Government and the National Grid for the operation of the pilot zone. Following the signature the management company is now looking for expertise on marine infrastructure, engineering, cabling and mooring to make the Wave Pilot Zone in Portugal operational [51].

There are also parallel activities which are in their embryonic stages for providing similar facilities of a one-stop-shop – *deploy and plug* – for marine current energy conversion devices. Some of these are likely to be around the UK's Channel Islands and the Isle of Wight, France, Canada, Taiwan and perhaps South Korea. Although these development are a welcome addition to the facilities provided for the exploitation of wave and marine current energy, their fate in the current financial climate is currently uncertain.

5.2. Plugging the knowledge gap

The wave and marine current energy conversion technologies are progressing at an appreciable speed. However, there is a paucity of in situ operational experience, coupled with the need to provide clear fundamental understanding to technology pioneers that can help advance their technology development and deployment plans. Fundamental research and development will have to bridge or plug the current gap in operational knowledge by utilising testing methodologies and tools for assessing devices at their early stage of development and providing the understanding needed for design and operations in arrays. A brief review of some of the

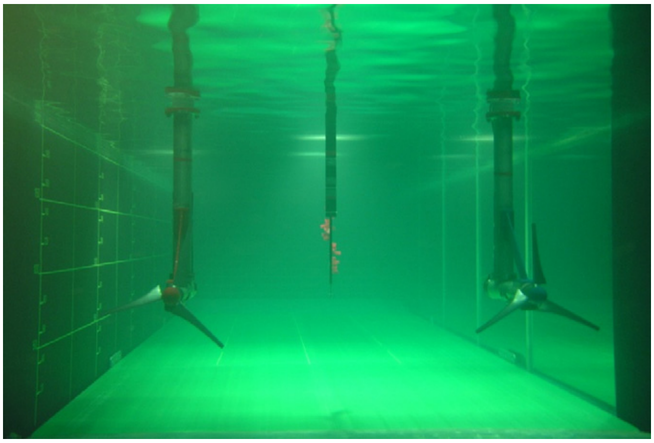

Fig. 14. Dual rotor model marine current turbine under test in circulating water channel [35].

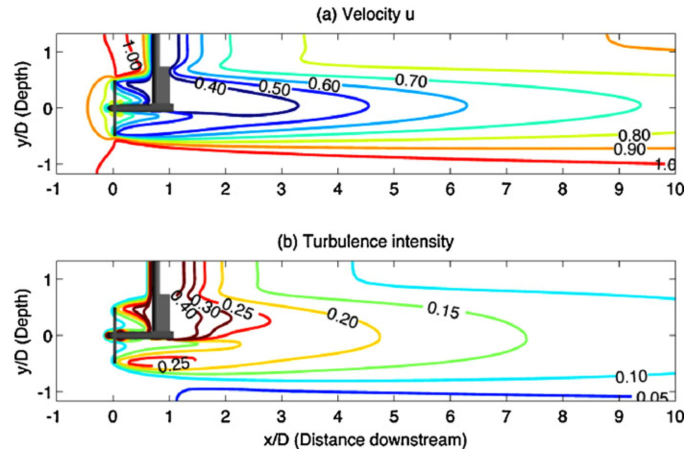

Fig. 16. Normalised velocity and turbulence intensity contours in the wake of a tidal stream turbine, modelled using a RANS-blade element solver [56].

issues is given in [43]. Hence, in parallel with the developments in the commercial sector (see Section 8), many aspects of wave and marine current energy conversion remains active areas of research.

As indicated earlier, there are no farms or arrays of multiple devices operating in the sea, hence fundamental research on model devices when coupled with numerical simulation can provide an insight into the design and operation of device in farms or arrays. As highlighted above, this research divides naturally between fundamental understanding; research on individual devices; device interactions and resource assessment.

Fig. 14 shows the University of Southampton's model testing of twin turbines conducted at the IFREMER facility in France (see Section 4.3). Extensive tests were carried on single rotors and side-by-side dual 0.8 m rotors within this facility [35]. Fig. 15 shows some of the results for the depth profile of velocity deficit at 5 diameters downstream of the turbines. Data is presented for each rotor and also for the centreline of the flume. The Gaussian velocity profiles downstream of the turbines are typical at this distance and the acceleration between the rotors can be seen clearly. Such tests were part of a UK funded programme to determine wake interactions and device spacing in arrays [52]. These results demonstrate the potential that closely spaced devices are likely to lead to local flow acceleration within the array's spatial footprint. Hence this work will inform future array design. Furthermore, several teams around the world are also working on CFD simulations of tidal turbines, using a variety of methods, linked to experimental results [53–55].

Figs. 16 and 17 provide examples of the University of Southampton's current work that addresses wake effects and combines simulation of modelled turbines validated by experimental data that can be utilised to give insight of wake and turbulence effects in marine current energy conversion. Numerical modelling has focused on the validation of a coupled solution of the Reynolds-averaged Navier–Stokes equations and blade element theory (RANS + BE) to model the flow around a marine current turbine [57]. This approach is used to derive the forces that the turbine applies to the flow and predict velocity deficit and turbulence intensity within the wake (Figs. 16 and 17). This approach was found to be computationally efficient and accurate in modelling both wake and performance characteristics of the turbine. The developed model is well suited to investigating wake effects in arrays of devices and other environmental effects.

Fig. 16(a) shows a significant reduction in velocity to 40% of free stream in the near wake behind the turbine, between 1 and 3 diameters (D) downstream. At 3D downstream the shear layers developing at the wake edges merge on the wake centreline, causing the velocities to start to rapidly recover, reaching 70% of free stream velocities by 9D downstream. In an array, if a turbine was placed within this slow moving flow it would have significantly reduced power output, demonstrating the requirement for increased downstream spacing in arrays, or a staggered array arrangement. Fig. 16(b) shows turbulence intensities in the wake of the turbine. These are highest immediately behind the

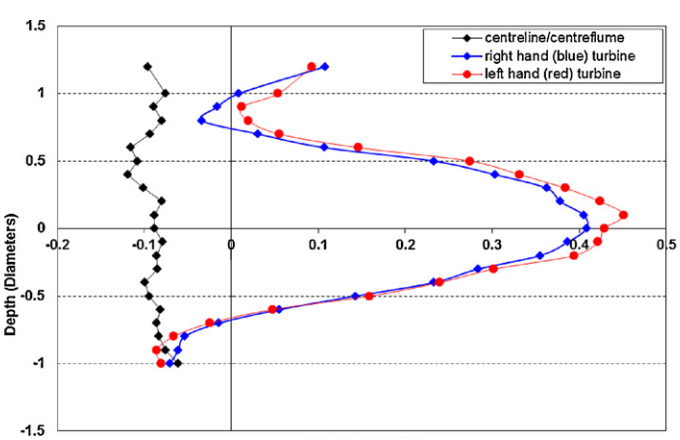

Fig. 15. Vertical velocity deficit profiles for dual rotor experiment, 5-diameters downstream, (rotors shown in Fig. 13).

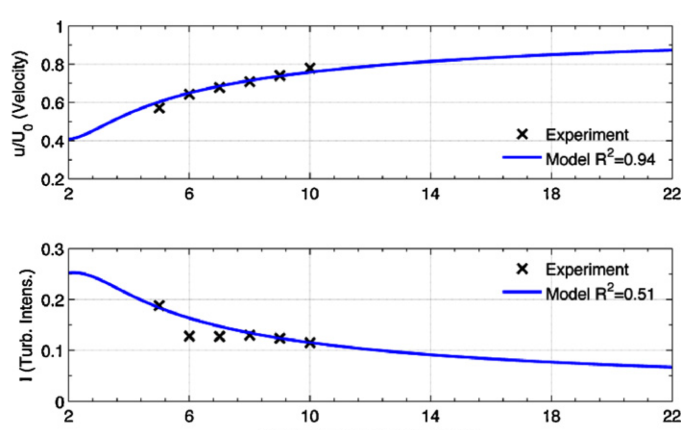

Fig. 17. Modelled centreline normalized velocity and turbulence intensity in the wake of a scaled marine current turbine, [57].

support structure, with velocities oscillating up to 40% from a time-averaged velocity. Further downstream turbulence intensities reduce, but remain high at 10% beyond 10D downstream. Placing a downstream turbine in regions of high turbulence intensity would have significant effects on blade loadings, and cause fatigue to the device.

The above approach was validated through our experimental data on tested model turbines. In Fig 17, the results of the model are compared to experimental data measured (at 0.8 m/s, and tip speed ratio of 8.4) in the wake of a 1/15th scaled model turbine mentioned earlier. The results depicted in Fig. 16 shows the centreline velocity and turbulence intensity on the centreline of the turbine wake, which has been modelled using RANS + BE and compared with measurement obtain experimentally. The results demonstrate excellent agreement in velocity values, and reasonable agreement between turbulence values up to 10D downstream. This demonstrates the fidelity of the model, and allows the results to be applied with confidence to a range of arrays and other environmental scenarios. Such modelling technique has also been applied to predict power output from arrays of marine current turbines at specific UK coastal locations such as Portland Bill [23].

6. Economic assessment

Economic assessment that addresses the potential of a device to achieve acceptable energy cost targets is extremely important not only for the economic viability of the technology but also to attract investment. Hence early modelling of the cost of generating electricity from a specific design philosophy is paramount and should form part of the development programme of the device and deployment projects (Fig. 1). Furthermore, since currently renewable energy technologies are under the lens in many countries, it is important that the economic competitiveness of wave and marine current technologies is coherently quantified. This will need to be done through appropriate but similar approaches undertaken by others in the renewables industry (wind, biomass, etc.) and taking into account any support mechanisms available for the technology. It is recognised that wave and marine current technologies are at an early stage of development and from the point of view of available finance, the plethora of conversion philosophies does not help. In addition, as this is a recent technology development, its current know-how does not provide ample experience from which accurate data can be utilised in economic modelling. Nevertheless, utilising economic approaches such as those used in offshore wind offer a good starting point to build on and enhance as further experience is gained from the deployment of wave and marine current devices.

Notwithstanding the above, there are now some considerable insights into economic assessment of marine energy technologies. Some notable examples are: the early assessment of wave energy by WaveNet, [58], the assessment of the cost of energy of wave and marine current devices undertaken by the Carbon Trust [59] and the economic assessment procedure defined by the Electric Power Research Institute (EPRI) [60]. A recent report which surveys current methodologies and their limits and also covering explanation of the risk factors involved in the calculation of the cost of energy can be found in [61]. The work of EquiMar, a European Commission funded consortium is producing a detail analysis of the cost of energy specifically related to wave and marine current energy conversion [62,63]. Such studies are important and are of benefit to the especially small enterprises developing the technologies.

7. UK approach for technology development and support

The UK is currently a worldleader in wave and marine current energy conversion technologies and their progressive development. This is partly due to:

- Dedicated advocates both from industry and academia who have invested time and effort to promote the relevance, applicability and research into the viability of the technology.
- The high level of the resources around UK's shores.
- The initial partial support by UK Government under its Technology Programme (2000–2007) to fund the needed research and support the development of technology prototypes.

To date, the UK has an overall spending for both wave and marine current energy of approximately £116 (US$175) million. This is in the form of research grants and other funding avenues for technology development established by central and devolved governments and the UK Research Councils. However, this funding is fragmented especially since 2007, when the previous government established a proliferation of funding entities to take its role in supporting the sector. Recognising this, the new UK Coalition Government, is in the process of abolishing some of these funding agencies and the uncertainty of how to replace these is likely to continue for the near future.

Most recently the Government published its Marine Energy Action Plan (MEAP) setting out an agreed vision for the marine energy sector to the year 2030 [64]. The plan which covers wave, marine current energy conversion and tidal range (now abandoned) outlines the actions required by both the private and public sectors to facilitate the development and deployment of marine energy technology and intends to fulfil the vision set out in the UK Renewable Energy Strategy and Low Carbon Industrial Strategy. The action plan envisages that by 2020, an installed capacity in the range 1–2 GW for both marine current and wave devices is feasible, rising to 2.5 GW by 2030 according to a conservative projection scenario. It is also postulated that marine renewable energy could play an important role in the period to 2020 as the sector begins to roll out larger arrays of devices [64]. This will be followed by large scale deployment beyond 2020 that will (a) help to meet the Government's commitment to achieve an 80% cut in the UK's carbon emissions by 2050 and (b) will create a new and successful UK low carbon industry.

7.1. Support instruments and incentives

The Renewables Obligation (RO) is currently the main mechanism for supporting large scale generation of renewable electricity [65]. This mechanism places an obligation on UK suppliers of electricity to source an increasing proportion of their electricity from renewable sources. Unlike a feed-in tariff, a Renewables Obligation Certificate (ROC) is a green certificate issued to an accredited generator for eligible renewable electricity generated within the UK and supplied to customers within the UK by a licensed electricity supplier.

One ROC is issued for each megawatt hour (MWh) of eligible renewable output generated – say from a wind farm. The value of such certificates varies in the devolve regions of the UK (Scotland and the Northern Ireland) from those set centrally by the central UK regulators – the Gas and Electricity Markets Authority (Ofgem). Such a mechanism, also called Government Orders, is applied on licensed electricity suppliers across England and Wales, Scotland and Northern Ireland. For 2010/11 the obligation is set at around 11%. Suppliers meet their obligations by presenting sufficient Renewables Obligation Certificates (ROCs) [65]. Where suppliers do not have sufficient ROCs to meet their obligations, they must pay an equivalent amount into a fund, the proceeds of which are paid back on a pro-rated basis to those suppliers that have presented ROCs. In essence the RO works by placing an obligation on licensed electricity suppliers to source a specified and annually increasing proportion of their electricity sales from renewable sources, or pay a penalty.

Since its introduction in 2002, the Renewable Obligation has succeeded in more than tripling the level of renewable electricity in the UK from 1.8% to 6.64% and is currently worth around £1.42 (US$2.13) billion/year in support to the renewable electricity industry [66].

In addition, special support through appropriately defined mechanisms, have been established in the UK targeting wave and marine current device developers to assist in bridging the funding gap (known as the "valley of death") between prototype and commercial devices. In August 2004 the Government set up the Marine Renewables Deployment Fund (MRDF) with a budget of £50 M (US$75 M) [67]. MRDF covers four components of marine energy: (i) wave and marine current energy demonstration scheme, (ii) environmental research, (iii) related research and (iv) infrastructure support. The wave and marine current energy demonstration scheme which accounts for £42 M of the MRDF's budget, was aimed at providing capital grants and revenue support to multi-device projects at early stage of commercial generation of power. In essence, this supports early prototype devices some could be at large scale testing facilities using technologies that have completed their R&D and are ready to move into a commercial environment. In 2007, the Scheme moved to an "open call" process in which applications could be received at any time. A recent (March 2010) written answer by a UK energy minster indicted that a total of £2.3 million has been disbursed from the (MRDF) through infrastructure and research projects since its inception in 2005 [68]. The stringent requirement imposed by the scheme coupled with sketchy readiness and availability of mature devices is the major hindrance to the utilisation of this support.

A further support for technology deployment was also initiated by the UK's Carbon Trust, named Marine Renewables Proving Fund (MRPF) [69]. This £22.5 million initiative will provide finance for the demonstration of promising wave and marine current energy devices, targeted at accelerating the leading and most promising marine devices towards the point where they can qualify for the Governments existing MRDF support scheme and, ultimately, be deployed at a commercial scale under the standard Renewables Obligation. The intention of MRPF is faster progress in technology deployment and lower risk investment propositions for the private sector. Up to £6 million was made available to successful applicants (providing up to 60% of the eligible project costs, with the rest to be matched by technology developers and their partners) to help meet the capital costs of building and deploying wave and marine current prototypes. The scheme stipulates that work programmes must be completed by 31 March 2011, and be scheduled for deployment in UK waters [69].

Recently (October 2010), the new Coalition Government in the UK announced its Spending Review which fixes spending budgets for each Government department up to 2014-15. The review confirmed that support for RO will continue for the foreseeable future. In addition, and since its introduction, the RO has been subject to various reforms and improvements. The most significant are summarised below:

- In April 2009, the Government introduced the concept of technology banding, where different technologies can receive different levels of support. The aim of this approach was to provide a greater incentive to those technologies that are further from the market with potential to deploy on a large scale [70].
- However, this banding was initially targeted towards off-shore wind; where previously, 1 ROC was issued for each megawatt hour (MWh) of eligible generation, regardless of technology. The changes introduced from 1 April 2009, allow new generators joining the RO to receive different numbers of ROCs, depending on their costs and potential for large-scale deployment. For example, onshore wind continues to receive 1 ROC/MWh, offshore wind currently receives 2 ROCs/MWh, and energy crops 2 ROCs/MWh.
- In April 2010, the RO qualifying period was extended by ten years from its current end date of 2027 to 2037 for new projects. The aim was to provide greater long-term certainty for investors, and an increase in support for offshore wind projects meeting certain criteria.
- In November 2010, the Government department responsible for the obligation (Department of Energy &Climate Change, DECC) has launched a consultation for the RO banding scheme that will inform the banding review scheduled for 2013 [70].

7.2. Impact on marine energy technology development

Although the vision of the Marine Energy Action Plan (MEAP) provides some level of optimism for all marine energy conversion technologies, the current Renewable Obligation mechanism may fall short in achieving such targets. The main obstacle is that most of the successful development and deployment at device pilot scale so far has been conducted by small companies supported by funds gained through high risk venture capital. Such endeavour indicates a current prototype cost ranging from £7–£10 million (US$ 11–15 million) per MW installed. However, the first deployment of multiple devices in arrays or farms, at say around £6M/MW (US$9 M/MW), will necessitate an order of magnitude greater capital investment, which is unlikely to be achieved through the current approaches of raising funds and the likely income generated under current RO maximum band of 2 ROCs.

Many industry supporters are now campaigning (through the consultation process) for a higher support for marine energy, requesting a 5 ROCs/MWh (as the case currently in the Devolved Government in Scotland), coupled with a 50% capital grant for first installed technology variants of marine energy projects across the UK. However, within the current economic climate and the recognition by the Government that any level of support will need to take into account the impact of increasing energy prices on the consumers, it is not clear whether this suggested level of support can be achieved. Therefore, a compromise is more likely to happen.

8. Prototype and commercial devices

In marine current energy conversion, to the author's knowledge, there is currently no commercially operated capacity in the world. However, in terms of prototypes operating at anticipated future commercial device capacities, there are notable installations within the UK and elsewhere. In addition, the UK has a distinct lead which supports world leading academic communities and testing infrastructure that not only aids the world highest concentration of technology developers but also act a nucleus for overseas developers.

A survey of publicly available information on commercial, prototype device development and deployment in the UK indicates buoyant but fund-limited activities. Tables 1 and 2 list the various developers and their projects, limited to the front runners in marine current and wave energy conversion respectively. Some of the highlights are bulleted below:

- Project SeaGen (Marine Current Turbines Ltd) at Strangford Lough, Northern Ireland, UK, was successfully deployed in 2008 (Fig. 18). This is a second generation device consisting of a piled twin rotor two-bladed horizontal axis turbine converter of an installed capacity 1.2 MW [71]. SeaGen reports that the systems are now working well, in spite of initial delays, re-design of the piling process and a blade failure encountered in the early stages of the deployment [72]. This is the world's first commercial scale tidal turbine prototype to generate electricity onto the grid inde-

Table 1
Publicly available information on commercial, prototype device development and deployment mainly in the UK. The table list for current front runners in marine current energy conversion.

Company	Project	Client	Location	Technology	Project capacity (MW)	No. of machines	Status
Marine Current Turbine [www.marineturbines.com]	SeaGen, UK	MCT	Strangford Lough, Northern Ireland, UK. Global first > MW scale deployment	16 m, side-by-side twin rotors, twin-bladed, mounted on a crossbeam, which can be raised on a surface piercing pile	1.2	1	Operational, 2008
	The Skerries, UK	npower	Wales - off the coast of the Welsh island of Anglesey in a fast flowing patch of 25 m deep open sea known as The Skerries	As above	10.5	7	2013/14
	Canada	Minas Basin Pulp and Power	Bay of Fundy in Nova Scotia, Canada	As above	1.5		No data
	Kyle Rhea, UK		Investigating the feasibility of a tidal farm in Kyle Rhea, a strait of water between the Isle of Skye and the Scottish mainland	As above	5	4	2013
	Brough Ness, UK	Crown Estate	Part of the project lead by the UK's Crown Estate in the Pentland Firth, Scotland. Brough Ness, on the southernmost tip of the Orkney Islands (South Ronaldsay) and north east of John O'Groats	As above	99	66	2017/2020
	Antrim, UK	ESB International/MCT	Off the Antrim (Northern Ireland) coast, UK (announced 9/2010)	As above	100	100	2018
OpenHydro [www.openhydro.com]	EMEC, UK	OpenHydro	European Marine Energy Centre (EMEC). First deployment of MCEC device, grid connected in the UK	6 m, open centred multi-blade turbine, mounted between twin surface piercing piles	0.25		Testing, 2006
	Bay of Fundy, Canada	Nova Scotia Power	Minas Passage of the Bay of Fundy (installed Nov 2009). Early planning started in 2010 for further installations, option for 65 MW	10 m, open centred turbine	1		Damaged, removed 11/6/2010
	Alderney, UK	Alderney Renewable Energy	Alderney's territorial waters.	No data, open centred turbine	No data	No data	No data
	Cotes d'Armor, France	EDF	Paimpol-Brehat (Cotes d'Armor) site, in north west France	16 m, open centred turbine	2–4	4	2011/12
	Scotland, UK	Airtricity (Scottish & Southern Energy)	Part of the project lead by the UK's Crown Estate in the Pentland Firth, Scotland	Open centred turbine	100	No data	To 2020
Atlantis [www.atlantis-resources-corporation.com]	EMEC, UK	Atlantis Resources Corporation	European Marine Energy Centre (EMEC). First deployment by the company in UK.	18 m, twin rotor, back-to-back, direct drive turbines (AK-1000), gravity, piled or floating	1	1	Aug 2010. Withdrawn (Nov 2010) due to total parting of the composite material from blade structures. New date 2011
	Project Blue, UK	Crown Estate	Part of the project lead by the UK's Crown Estate in the Pentland Firth, Scotland	As above	30	30	No data

Table 2
Publicly available information on commercial, prototype device development and deployment mainly in the UK. The Table list for current front runners in wave energy conversion.

Company	Project	Client	Location	Technology	Project capacity (MW)	No. of machines	Status
Pelamis Wave Power Ltd [www.pelamiswave.com]	Agu doura, Portugal	Enersis/Babcock & Brown	5 km off the Atlantic coastline of northern Portugal, Autumn 2008.	Pelamis P1 (750 kW), 135 m long, 3.5 m wide articulated cylinders, ride and fall with the waves	2.25	3	Suspended in 2009
	E.ON at EMEC, UK	E.ON UK	EMEC North berth, 2 km west of Orkney Mainland. 1st stage of deployments	Pelamis P2, 180 m long, 3.5 m wide connected cylinders, ride and fall with the waves	0.75	1	Testing, 2010
	SPR at EMEC, UK	Scottish Power Renewables	EMEC North middle berth, 2 km off the west coast of the Orkney mainland, Scotland	As above	0.75	1	Order placed March 2010
	Aegir – Shetland, UK	Vattenfall	1–10 km off the west coast of mainland Shetland, Scotland	As above	20	26	Commissioning to start 2014
	Bernera Wave Farm	Pelamis Wave Power	Off the west coast of Great Bernera, Western Isles, Scotland	As above	20	26	Currently in scoping stage
	Farr Point Wave Farm, UK	Pelamis Wave Power	Off the north coast of Sutherland, Scotland. Part of the Pentland Firth UK's Crown Estate. Phase 1–7.5 MW/Phase 2 – up to 50 MW	As above	50	66	Agreement for lease awarded from The Crown Estate. Phase 1 grid connection agreed
Aquamarine Power [www.aquamarinepower.com]	EMEC	Aquamarine Power	EMEC's Billia Croo site near Stromness	A mechanical flap that sways with the waves driving hydraulic pistons to pressurise water onshore to drive a turbine. The flap is hinged to a base structure mounted on the seabed	0.35	1	Oyster1 - Under test, 2010
	EMEC	Aquamarine Power	EMEC's Billia Croo site near Stromness	As above, consist of three linked devices = Oyster2	2.5	1	Currently in development
	Pentland Firth	Various - see Table X	Pentland Firth and Orkney Waters Round 1 Development Sites - see Table X	As above, but may consist of linked devices	550	No data	By 2020
Wave Dragon [79]	Wales	Wave Dragon	2–3 miles off the South West Wales coast, off Milford Haven, and covers an area of approximately 0.25 km 2. 7 MW – demonstration	Overtopping device. Waves overtop a ramp raising the water to a reservoir, creating a 'head' of water which is released through a number of turbines.	7	1	Planning application submitted
Wavegen [80]	Islay	Wavegen	Island of Islay, Scotland	Oscillating Water Column	0.5		Operating at a demonstrator
	SWEP	npower (2009) - Siadar Project.	Isle of Lewis in the Outer Hebrides - an "active breakwater"	As above	4		Currently in development
	Spain	Basque Government	Basque town of Mutriku – Spain	As above	0.296		Currently in development

Fig. 18. SeaGen 1.2 MW, twin rotor, 2 bladed turbine installed in Strangford Lough in April 2008, with crossarm raised (image courtesy of MCT Ltd [71].

pendent from a test centre (see also Table 1 for details on future projects).

- The Irish company OpenHydro has been testing their open centred, rim generator device, capacity 250 kW, at the European Marine Energy Centre (EMEC) in the Orkneys for around three years (Fig. 19). No news has been forthcoming on performance [73]. The company seemed to be negotiating a project in France with EDF, but this has not been formally announced (see also Table 1 for details on future projects).
- The first grid connected 100 kW shallow-water tidal current device which uses oscillating hydrofoils that lie horizontally in the water and sweep up and down in the flow was installed in 2009 by Pulse Tidal Ltd in the Humber Estuary, UK [74]. The device installed in 9 m of water depth is going through its testing phases and supplying electricity to a large chemical plant on the South bank of the estuary. The company indicated that their next phase will be a commercial deployment of their device within the Isle of Skye waters starting 2012.
- Atlantis Resources Corp, in August 2010 deployed a 1 MW device at EMEC, Fig. 20, [75]. But the device was subsequently removed due to blade failure. This is clearly a setback for the company and its plans for the future. However, the company indicated that the limited exercise provided ample experience in deployment of their device (see also Table 1 for details on future projects).

Fig. 20. Atlantis Resources Corp 1 MW, back-to-back twin rotor device prior to installation at the European Marine Energy Centre [75].

- Tidal Generation Limited, now owned by Rolls Royce Plc. is developing a deep-water device to be deployed at EMEC in 2012. The initial phase of installing the tripod foundations of this 0.5 MW tidal turbine was accomplished early in 2010 [46].
- Pelamis Wave Power Ltd has a selection of projects that build on its P1 machines. As indicated earlier and shown in Table 2, Pelamis, was has the world's first array of 3 P1 (750 kW capacity each, 135 m long, 3.5 m wide connected cylinders, ride and fall with the waves) machines in the ill-fated project established 5 km off the Atlantic coastline of northern Portugal in the Autumn of 2008. The company is now progression with new generation machines P2 (see Fig. 21) of a similar capacity through a rigorous testing programme at EMEC.
- Aquamarine Power has now established itself with support from utilities within the UK as major player in wave energy conversion [77]. Its wave energy converter, named the Oyster, encompasses a buoyant mechanical surface piercing flap hinged at the sea bed that sways with the waves driving hydraulic pistons to pressurise sea water onshore to drive a turbine. The flap is hinged to a base structure mounted on the seabed [78]. It has installed its 350 kW first prototype at EMEC in 2009 (Fig. 22) and the company is now working on development of its second generation device, Oyster2 [77].
- The other noteworthy wave energy device developers are Wave Dragon [79] and Wavegen [80]. Available details on their development programmes are shown in Table 2.

Fig. 19. OpenHydro 250 kW open centred, rim generator device, undertaking tests at the European Marine Energy Centre [73].

Fig. 21. Pelamis Wave Power Ltd., 750 kW P2 undertaking tests at the European Marine Energy Centre (Image Courtesy of PWP Ltd [76].

Table 3
Pentland Firth and Orkney Waters Round 1 Development Sites, 1200 MW initially announced in March 2010 (SSE = Scottish and Southern Energy, Oyster = Aquamarine, MCT = Marine Current Turbine, TGL = Tidal Generation Ltd).

Project type	Project developer	Project location	Technology to be used	Capacity MW
Wave energy device total capacity 600 MW	SSE Renewables Developments	Costa Head	Oyster	200
	Aquamarine Power & SSE Renewables Developments	Brough Head	Oyster	200
	Scottish Power Renewables UK	Marwick Head	Oyster	50
	E.ON	West Orkney South	Oyster	50
	E.ON	West Orkney Middle South	Oyster	50
	Pelamis Wave Power	Farr Point	Pelamis, P2	50
Marine current energy device total capacity 600 MW	SSE Renewables Developments	Westray South		200
	SSE Renewables & OpenHydro	Cantick Head	OpenHydro	200
	Marine Current Turbines	Brough Ness	MCT, SeaGen	100
	Scottish Power Renewables UK	Ness of Duncansby	MCT, SeaGen	100
	MeyGen (Oct 2010)	Inner Sound	Atlantis and TGL	400

9. Future prospects

The impetus for deployment of wave and marine current technology does not seem to be (from the developers' point of view) dented by the financial crises. Over the last two years several developers were eyeing the Pentland Firth, Scotland, UK, for commercial scale deployments. The Crown Estate, which owns the seabed around UK coast, provides site options and leases for projects. Recently it has announced the results of Round 1 Pentland Firth and Orkney waters, summarised in Table 3. Ten demonstration and commercial projects totalling 1.2 GW of potential capacity of different technologies (600 MW wave energy devices, 600 MW marine current devices) at an estimated cost of approximately £4bn (US$7bn) are planned to be installed by 2020 [81]. In addition, the highlighted schemes will require up to £1bn (US$1.5bn) of extra investment – from public sources – to develop and build new grid connections, harbours and other infrastructure in Orkney and Caithness. The idea behind this venture is that the Crown Estate will support these activities as a partner transcending bottle-neck issues such as permitting, consenting and financial support. However, a lot more will need to be in place (e.g. ROC support) to achieve the highlighted capacity for the sites.

Looking further into the future, there seem to be few significant activities in developing or accelerating projects at array or farm scale for exploiting marine current energy. In March 2008, Lunar Energy announced that it had signed a Memorandum of Understanding with Korean Midland Power to develop a 300 MW farm in the South Korea by 2015. If this project goes ahead it will by far be the largest marine current development in the world [82]. However, to date the fate project is currently unknown! In addition, Korea also has two other projects: firstly a newly installed 254 MW tidal barrage scheme retro-fitted into an existing 11 km barrage in Sihwa Lake, completed in 2010 [83] and secondly, a plan for converting three barrages, total capacity of 1.8 GW, by 2014 [84]. These developments will launch Korea as the world's leading nation for tidal energy generation.

Fig. 22. Aquamarine power's oyster wave power technology, capacity 350 MW (Image courtesy of Aquamarine Power).

For wave energy conversion, and in addition to deployment highlighted in Tables 1–3, the facilities discussed in Section 5, such as the Wave Hub (UK) and Wave Pilot Zone (Portugal) are likely to create considerable interest from developers enhancing announce capacities in the not too distant future.

10. Discussions and conclusions

This work provided an overarching analysis of the salient issues related to the conversion of wave and marine current energy resources. It establishes a step-by-step approach that could be used in technology and project development, depicting important results derived from experimental and field observations on device fundamentals, modelling approaches, resource assessment, sites and projects developments.

Fundamental research is highlighted as providing an important role to address the paucity of field experience. Relevant data from such research is given in the paper as examples to support such a role. As most technology developments are currently UK based, this work also highlighted technology support mechanisms available and provided context of these to future technology development.

Given all the above, there are also other important issues that will need addressing:

1. Most important is that the technology must prove itself within the operating environment. That is, there is an urgent need to gain operational experience in the sea. This experience is paramount as it gives confidence to investors, energy utilities and governments in the viability of the technology.
2. The viability of the technology will depend, in the long term on operational reliability of the devices, their maintenance and operating costs, permitting and consent for projects, availability of ports and grid infrastructure and most importantly (in the age of the current credit crunch) the availability of finance.
3. In the UK, there is a paucity of domestic manufacturing capacity for both systems and components. The UK will need to build up a capacity in these areas to avoid a similar fate of off-shore wind supply chain of which most of the predicted UK expansion is likely to be supplied from overseas.
4. Technology developers and stakeholders will need to establish a robust supply chain for design and manufacture, transport to site and appropriate installation vessels.
5. As technologies developed and deployment expanded, the issue of reliability, maintenance and role of design of components and

their servicing schedules, will become important. The role of tribology in the longevity of device will also need to be considered [85].

6. There are however, many drivers that are likely to play a major role in assisting the development and the roll out of ocean energy technology. These initiatives are mostly related to new energy and climate change legislation in many countries, the prevalence of feed-in tariffs in many EU countries, the change in policy in the USA, the requirements for energy security and fulfilling internationally negotiated carbon reductions.

However, it is also recognised that one of the major barriers for the wave and marine current energy conversion technologies is the cost per MW installed. This is currently in the range £7–£10 million (US$ 11–15 million), with the lower value for multi-MW installations and the higher for a single commercial prototype. A pathway to cost reduction to attain future parity to the currently acceptable cost of £3 million per MW for offshore wind will need to be found by developers either through economy of scale or by optimising, streamlining devices and their operation and maintenance.

Nevertheless, and as indicated earlier, we have recently seen important clear milestones for ocean energy conversion. We have seen the first deployment of three grid connected, large scale pre-commercial devices in the sea, albeit limited to sheltered test sites. In addition in the UK we have seen entities like the Crown Estates take a lead on site development building on approaches applied for offshore wind site development. Sites such as the Wave Hub and Wave Pilot Zone will also provide impetus for technology deployment. Such progress is extremely important for the technology as it has stimulated many activities including joined-up thinking for developing sites with arrays or farms around the world.

Although the above developments are much welcomed there is perceived unease in the UK about the role of the Crown Estates which some feel may create a conflict of interest. That is currently the Crown Estates is the sea bed owners, yet at the same time it is taking the role of a project developer. In addition, recently other new entities with similar roles as the Crown Estates have been created through new regulation within the UK – e.g. the Marine Management Organisation (MMO) created under the 2010 Marine and Coastal Access Act. MMO are the new manager and regulator of England's marine environment and will deliver the key actions set out by the Act. Such diffusion of responsibility will undoubtedly create bottlenecks and will at least in the earlier stages of defining the roles of these entities, be another barrier to deployment.

The change of administration in the USA has heralded a new impetus for the ocean energy sector. The ambitious funding of US $18.5 billion for renewables [86], may also help to awaken other countries to invest in such areas for the creation of jobs and the exploitation of non-fossil fuel sources for electricity production, notwithstanding the unfavourable economic climate. This will have implications for the current lead enjoyed by the UK.

As indicated above, the UK has a huge resource in wave and marine currents. At present, it also has a clear lead in wave and tidal energy conversion activities, which is a result of a first class research and development community both within universities and industry. This lead is however, under threat due to the inflexible and sometime incoherent support mechanisms for research, development and the route to commercialisation. As a society we also have responsibility for the young scientist and engineers currently devoting their early careers to the development of these technologies. Hence there is also a moral imperative for governments and institutions, such as the EU, to provide the crucially needed support to make this new technology a reality. It is also imperative that such support is gauged at appropriate levels to allow the exploitation of such sustainable resources for the benefit of society and the environment.

In summary, ocean energy technologies, limited here to marine current and wave energy conversion, and their associated industries are still in their infancy. Many observers believe that the current status of the technology is comparable with that of the emerging wind energy development in the 1980s. However, in the UK there is a concerted support for the technology at ministerial level and given the government's commitment to combat climate change, the establishment of favourable regulatory regimes, the progress should be much faster than that achieved for wind energy development.

However, one needs to be cautious about predicting such fast development. This is partly due to the characteristic of the resource, the infancy of the concepts currently employed for conversion and the deployment sites which provide different challenges than those of offshore wind. Furthermore, there is a plethora of conversion technologies with unconnected design philosophies that seem to dilute effort and compete for the scarcely available financial resources. These issues, in many cases, coupled with the fact that most developers are small enterprises with limited funds, has resulted in high inertia holding back a faster trajectory to accelerate technology commercialisation. It is therefore important to recognise that funding for deployment of multiple devices will be crucial in expediting the roll out of the technology. Without such support the pathway to commercialisation will be long.

Nevertheless, judging by the various activities reported here and other around the world, and consolidation provided by the entry to the market of electrical utilities and institutions like the UK's Crown Estate, there is further hope that the road to technology roll out will not be long, hence the future for wave and marine current energy conversion looks bright.

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